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EFFECT OF ALLOYING ELEMENTS ON HEAT-RESISTANT PROPERTIES
OF CHROMIUM STAINLESS STEELS

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[Numbers in parentheses refer to appended references. Tables and figures referred to are also appended.]

Introduction

To increase the economy of steam turbines it is most important to increase the initial steam parameters (temperature and pressure), which are limited by the inadequate strength of materials currently used in turbine building. Stationary boiler and turbine aggregates operating in steam temperatures of 565-650° and pressures of 130-300 atmospheres should be built in the next few years. The unit rating of turbines must be increased to 200,000-300,000 kilowatts. This poses serious problems to metallurgists in their quest for new, dependable, inexpensive, and suitable heat-resistant materials for new types of steam boilers and turbines.

The investigations described herein aimed at finding nonaustenitic blade materials which would satisfy specified conditions for service at temperatures up to 600° and which would be steel-based but would not contain any nickel. Chromium stainless steels 1Kh13 and 2Kh13 were used for many years in the production of steam turbine rotors and guide vanes operating at temperatures of up to 510° (1). These steels respond well to forging, rolling, and stamping; have high over-all corrosion resistance; do not tend toward intercrystalline corrosion in condensates; and, when hardened and tempered, have favorable mechanical properties. However, low heat resistance at temperature over 525° limits their application. Therefore, in the development of economic heat-resistant steels for use in high-parameter steam turbine blades, it is desirable to increase the heat resistance of such steels and to make them suitable for service at 565-600° by supplementary alloying.

In other countries, and especially in the US and England, experiments were conducted in the development of heat-resistant steels based on 12% chromium stainless steels. The chemical compositions of Soviet and foreign chromium steels are listed in Table 1.

In the development of high chromium heat-resistant steels, the researchers did not alloy with molybdenum and vanadium, with which it was possible to obtain the best heat-resistant properties in pearlitic steels with 1-3% Cr. Most of the steels contain only 0.10-0.30% V, but also have other alloying elements (W, Nb, Co). According to foreign data, only the H-46 steel (see Table 1), which is used for disks and other parts of gas, aviation, marine, and other turbines, contains 0.70% V and even its vanadium content, according to the latest data, was decreased to 0.3%.

An investigation (2) of the heat-resistant properties of 12% chromium steel containing niobium showed that an increase in the carbon content causes an increase in the rate of creep. The steel has optimum properties

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with a 0.15% C content. This conclusion is confirmed in practice. The table shows that the vast majority of steels contain 0.10-0.20% C. All the steels examined contained molybdenum. In alloying a stainless steel (0.2% C and 14.0% Cr) with molybdenum (3), the stress which causes a total deformation of 0.2% at 550° in 1,000 hours increased from 3 to 5.5 kg/mm². Nonetheless, the heat-resistant properties of steel remain too low for turbine parts operating at temperatures over 550°. To obtain higher heat-resistant characteristics, the molybdenum content of some steels is increased to 2.5-3% or, besides 0.5% Mo, other alloying elements are added (W, V, Nb). According to the literature (2-5), one of the most heat-resistant steels in the Rex 448 steel. Besides 0.7% Mo, it contains carbide-forming elements such as V (0.10-0.20%) and Nb (0.3-0.6%).

This steel is used for gas turbine blades and disks and has good mechanical properties at room and high temperatures up to 650° and good heat-resistant properties at temperatures up to 600° for service life not exceeding 1,000 hours. There is very little data on the behavior of this steel during longer service. The only data is that at 600° and a stress of about 7 kg/mm², after 10,000 hours, its total deformation is 0.2%.

In the US, despite the shortage of tungsten, steels of this class, which contain up to 3.0% W, are used. There is a lack of data in the literature on the effect that tungsten has on the properties of 12% chromium steels.

Existing data permit the conclusion that, despite the importance of the practical application of 12% chromium steels having additional admixtures, there is no systematic investigation of the effect of individual hardening elements on the structure and properties of this type of steel. There is also no satisfactory explanation of the effect of the more important of these elements on heat-resistant properties.

Experimental Section

The experiments were based on a chromium-molybdenum stainless steel having the following chemical composition: 0.10-0.15% C; 10.0-12.0% Cr; and 0.6-0.8% Mo. After hardening and high tempering the steel had a sorbitic structure (see Figure 1). Both strong carbide-forming elements (Nb, Ti) and elements which are easily soluble in ferrite (V, W) were investigated for supplementary alloying. The alloying elements were introduced in sufficiently wide limits (Table 2), both separately and together.

The steel was smelted in an induction furnace having a basic lining. Each heat was separated into three parts, which differed in their content of one element; this element was added after the pouring of the previous part. Thus, three steel compositions were obtained from each heat, forming a series having the same base.

Ingots 12 kg in weight were forged into rods and heat-treated as follows: hardened at 1,050°, soaked for one hour, cooled in oil, tempered at 650°, soaked for 3 hours, and subsequently air-cooled. The heat-treatment was selected on the basis of an investigation of dilatometric curves as well as the structure and hardness of steel after experimental hardening at various temperatures. The heat-treatment used assured a grain size of No 6-8 of the normal scale in all the steels. Thus, the chance of varying initial grain sizes affecting the properties of the steel was averted.

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In the supplementary alloying of the steel with vanadium, tungsten, niobium, or titanium, the structure becomes less homogeneous. Individual inclusions of ferrite appear; moreover, when the content of the alloying element is increased, their number and area also increase. The increase in the quantity of ferrite is most noticeable in the structure of steel containing niobium or titanium. Thus, the structure of steel containing more than 0.7% Nb (the composition of KN-3), consists basically of large ferritic grains; sorbite is present only in the form of individual areas situated along the granular boundaries (Figure 2).

Mechanical properties were determined at 20, 600, and 630°. At all the temperatures investigated, an increase in the content of the alloying elements caused a continual decrease in the hardness characteristics of the steel, which is related to the increase of ferrite in the steel structure. Hardness and strength are most noticeably decreased in a steel alloyed with niobium and titanium (Figures 3 and 4). When vanadium content is increased, similar results are observed in the steel, although the effect of the vanadium is considerably less and is apparent only when its content is over 0.3%. The effect of tungsten merits special attention. Alloying with tungsten up to 4.0% hardly decreases the strength properties, despite the increase in ferritic content (Figure 5). The strength of steels containing, besides the tungsten, up to 0.4% Nb is also decreased (Figure 6).

The effect of the alloying elements, except titanium, on the plastic properties of steel is markedly less. The introduction of ~0.1% Ti into steel considerably lowers its plasticity, while in the other steels the plasticity remains high. The impact strength at high temperatures (600°) as a rule increases as the content of the alloying element is increased. All the steels investigated had high impact strength at room temperature. The exceptions were the KN-8 (0.4% Nb, 3.4% W) and KN-3 (0.7% Nb) heats, in which the impact strength dropped to 1.3 and 2.1 kgm/cm², respectively. Such an impairment in the properties is explained by the fact that in the steels investigated, which were nearly entirely ferritic, there was an almost complete lack of phase transformations; therefore the increase in grain size after heat-treatment and forging is greatly apparent.

Circular specimens were used to test the steels for creep; the I. A. Oding method was used at 550, 600, and 630° and at various stresses (4, 6 and 8 kg/mm²). Specimens of all the steels investigated were tested for at least 1,000 hours. An analysis of the primary creep curves shows that the variation of values for parallel specimens was relatively small. Very frequently their values fell into one curve. Figures 7 and 8 show some of the graphs of the relationship of creep to alloying element content. Creep rates of specimens tested for 600-1,000 hours were used in plotting the curves. To determine the mechanics of the effect of alloying elements on the heat-resistant properties of steel, an extended investigation of the carbide phase was conducted (Table 3). The chemical composition of ferrite is listed in Table 4.

The investigation of a 12% Cr-Mo steel for creep showed that it is insufficiently heat-resistant in the range of 550-600°. The investigation of the composition of the carbide phase of steel showed that, in the presence of a large amount of chromium (12%), vanadium remains principally in solid solution, forming an insignificant amount of the carbide VC, in which is combined not over 10% of the total vanadium content of the steel. In the tempering and aging from the solid solution of these steels, there is separated a chromium carbide Me₂₃C₆, in which a large amount of the molybdenum is dissolved (up to 25% of its content in the steel).

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Because of the impoverishment of the solid solution by molybdenum and the possible weakening of the intracrystalline bonds in the ferrite crystals, owing to the vanadium dissolved in it -- and this is indicated in the literature (6) -- with a high content of the latter, the heat-resistant properties of steel fall sharply; this is even more apparent if the test temperature is increased to 600-630° (Figure 7). However, if alloyed with small admixtures of vanadium (up to 0.3%), the resistance to deformation of 12% Cr-Mo steel is considerably increased over the whole range of the temperatures investigated. This is explained by the fact that the presence of a small amount of vanadium in the carbides and the solid solution to some extent stabilizes the solid solution. This is confirmed particularly by the fact that under lengthy aging (up to 10,000 hours at 600°), the relative molybdenum content in the solid solution and the carbides remains practically unchanged by comparison with the initial (Table 4).

Thus, the role played by vanadium in the 12% Cr-Mo steels, as a result of the effect of the law of active masses during phase formation, is entirely different from its role in the common 1-3% Cr-Mo steels in which the vanadium is the basic carbide-forming element, which permits the retention of the molybdenum in solid solution and therefore maintains the high heat-resistance of this class of steels. Inasmuch as there is an increase in the heat-resistant properties of 12% Cr-Mo steel when ~0.3% V is introduced into it, steel having the following composition was selected as the basis for composition investigations: 0.10-0.15% C; 10-12% Cr; 0.6-0.8% Mo; and 0.2-0.3% V.

The investigation of the effect of admixtures of the strongest carbide-forming element, titanium, on the structures and properties of steel showed that when the Ti content is increased from 0.15% to 0.55% the quantity of ferrite in the steel is greatly increased and the mechanical properties decreased. An analysis of the carbide phase shows that, in the presence of titanium, there is formed a special TiC carbide, the TiN nitride and chromium carbide Me_23C_6 . According to data which still require additional checking, about 30% of the total titanium content of steel, in the initial state and after aging, is in solid solution if the Ti content is over 0.10%. The molybdenum content in the carbide phase is decreased in the presence of titanium as the content of the latter is increased (from 23 to 10% of the molybdenum content of the steel).

The stability of the solid solution (ferrite) in the presence of titanium is increased, which is generally confirmed by phase analysis data both before and after aging for 10,000 hours at 600°. However, apparently because of the impoverishment of the solid solution by the carbon, its strength decreases, and this explains the decrease in the resistance to creep at a relatively low temperature (550° and 8 kg/mm²) in steels containing more than 0.1% Ti.

At 600° titanium has practically no effect on the creep resistance of steel (Figure 8).

At higher temperatures (630°) and comparatively low stress (4 kg/mm²), the stability of the solid solution becomes the decisive factor, assuring a relative increase in the resistance to creep of steel when its titanium content is increased.

The data obtained permit the conclusion that the alloying of 12% Mo-V steels with titanium does not make it possible to obtain steel sufficiently heat-resistant for service at 550-600°.

A study of the effect of another carbide-forming element (niobium, up to 0.7%) on the structure and properties of steel shows that, when its content is increased, the ferrite constituent in the steel structure is also increased as

much as in steels containing titanium. The strength properties and the impact strength are simultaneously decreased. Of greatest interest is the study of creep resistance of steels with varying niobium contents.

Thus, the introduction of even 0.15% niobium into steel considerably increases the creep resistance of the steel in the temperature range of 600-630° and under relatively low (6-4 kg/mm²) stresses (Figure 8). With the subsequent increase in niobium content to 0.45-0.71%, the rate of creep at 600° continues to decrease and only at 630° does a niobium content beyond 0.45% cause a sharp softening of the steel.

In analyzing the carbide phase it was established that, as the niobium content of steel was increased, the quantity of chromium carbides Me_2C_6 is sharply decreased and MeC becomes the basic carbide separated from the solid solution. Moreover, the molybdenum content of the solid solution is continually increased from 87 to 98% of its total content in the steel at the expense of its decrease in the carbide phase. During lengthy aging (10,000 hours at 600°) an additional decrease is observed in the chromium content of the carbides and an increase in the molybdenum and niobium content.

Unlike titanium, niobium apparently does not enter into the composition of the ferrite but remains entirely in the carbide phase. The great stability of the solid solution of ferrite in the presence of niobium (when its content is up to 0.45%) assures a considerable increase in creep resistance.

Of greatest interest are the series of steels alloyed with tungsten (either with or without niobium). Tungsten, as is molybdenum, is among the elements easily dissolved in ferrite at room and high temperatures. The large atomic radius of this element results in great distortions in its crystalline lattice. Nonetheless, as is known, tungsten is a lesser carbide-forming element than vanadium, titanium, or niobium.

The creep resistance of steels containing tungsten increases as the tungsten content is increased, with the greatest strengthening effect obtained at 600°. At a lower temperature (550°) the effect of the tungsten is significantly less. Of all the steel compositions investigated, the smallest rate of creep ($0.6 \times 10^{-5}\%$ /hour) at 600° and 6 kg/mm² was in a steel containing about 4% W (Figure 8).

With the simultaneous presence of niobium (~0.4%) and tungsten (up to 1.5%) in steel, the effect of the latter on the resistance to small plastic deformations is less noticeable. But, as seen from Figure 9, when the tungsten content is increased to 4.0%, the rated creep strength (for a rate of $1 \times 10^{-3}\%$ /hour) increases sharply. Thus, with a high tungsten content, the effect of niobium on the heat-resistant properties is greatly decreased, and such properties remain at the same level as in steels containing tungsten but no niobium.

The test results for continuous strength at a temperature of 600° and a stress of 11 kg/mm² are presented in Table 5.

An analysis of the data presented shows that all the steels investigated maintain their high plasticity during long-run tests. In comparing the time to destruction of steel specimens of various compositions it may be seen that these data generally conform with the creep test results. The fact that titanium is not a very effective element is particularly verified.

With increase in the vanadium content, the long-run strength of steel decreases.

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Niobium-series steels have relatively good properties. However, if the niobium content is high (0.7%) the strength properties are decreased and are practically the same as those of the 12% Cr-Mo steel, which attests to the insufficient strength of a low-alloyed basic solid solution (ferrite).

Steel with a 3.5% tungsten content has the maximum continuous strength. Thus, the great effect of tungsten in increasing creep resistance and continuous strength is apparent. Steels alloyed with tungsten, as was shown above, have very good mechanical properties. More detailed additional investigations were therefore conducted on steels supplementarily alloyed with tungsten as well as with tungsten and niobium.

Tests have shown that all the steels investigated are characterized by a high plasticity. For example, steel containing 3.4% W and 0.4% Nb, after destruction at 6,559 hours, had a relative elongation of 27.8% and a reduction in area of 56.0%; the destruction was intracrystalline. Curves have been plotted relating time to destruction to stress $\sigma_K = f(\sigma)$ in a logarithmic coordinate system, on the basis of test results. As seen from these curves (Figure 10), at 600° tungsten considerably increases continuous strength (60% for 10³ hours); moreover, its greatest value (16 kg/mm²) occurs with a 4% tin content. Steel not containing tungsten but having the same total content of other alloying elements has a continuous strength of ~7 kg/mm².

In the carbide precipitate of the tungsten-series steels not containing any niobium, when the tungsten content is increased to 4%, there is also found, besides the chromium carbide $Me_{23}C_6$, a complex carbide (Fe, Cr, W, Mo, V)_nC with an enlarged lattice parameter. The solid solution of these steels is, in the initial state (after hardening and tempering), very strongly alloyed with molybdenum and tungsten; it contains up to 90% Mo and over 90% W (of their content in the steel). After long-time aging (10,000 hours) at 600°, the chromium content of the carbide precipitate is somewhat decreased, the molybdenum content remains unchanged, while the tungsten increases (by about two times).

Roentgen ray analysis has still failed to show whether a new phase (Fe_2W) appears or whether the quantity of the complex carbide is increased.

An analysis of the carbide precipitate from the series of steels containing tungsten and niobium (~0.4% Nb) shows that NbC is the basic carbide in the initial state; all the Nb, moreover, is in the carbide precipitate. Besides the NbC, chromium carbide $Me_{23}C_6$ is present; no complex carbide is found in the steel after hardening and tempering. After aging (to 3,000 hours at 600°), the chromium content of the precipitate decreases, while the tungsten and iron content sharply increase, which means that a complex carbide other than $Me_{23}C_6$ or the compound Fe_2W is probably present in these steels.

It is still impossible to determine which phase, other than the carbide NbC, is present in steel since only weak, diffused lines appear on the roentgenogram.

A solid solution of these steels, even after long-time aging, contains a large amount of molybdenum and tungsten (over 70-80% Mo and 50-60% W of their total content in the steel).

Thus, alloying 12% Cr-Mo steels with tungsten is very effective. The tungsten is effective in that a considerable part of it goes into the α -solid solution, while the other part goes into special complex carbides. Tungsten

greatly strengthens ferrite at high temperatures, retards diffusion processes, and increases the temperature of recrystallization. In the presence of tungsten a considerable part of the molybdenum remains in solid solution.

The presence of a greatly strengthened solid solution and a sufficient quantity of the carbide phase assures high heat-resistant properties for 12% Cr-Mo steels which are alloyed with a large amount of tungsten. Nonetheless, besides favorable strength properties, these alloys have satisfactory plasticity and impact strength, which are maintained over a very long time interval at high temperature.

Steels containing tungsten and niobium are of interest since in their heat-resistant properties they are not inferior to, and are even superior to steels containing tungsten but no niobium, as a result of the even more stable solid solution. They are, however, almost entirely ferritic, which results in a considerable decrease in impact strength at room temperature and may cause difficulties in heat-treatment and welding.

Conclusions

The experiments conducted on the 12% Cr-Mo steels containing additional alloying elements permit the following conclusions.

1. The heat-resistant properties of steel are most effectively improved by alloying with tungsten; moreover, steel has the best properties when it contains about 4% tungsten.
2. Alloying with niobium increases the heat-resistant properties of steel if the niobium content does not exceed 0.45%. However, the heat resistance of such steels is lower than that of steels alloyed with tungsten (~4% W).
3. Alloying with both tungsten and niobium (~4% W and 0.4% Nb) increases heat-resistant properties somewhat more than does alloying with just tungsten, but the impact strength is decreased and difficulties emerge in heat-treatment.
4. Investigations showed that increased heat-resistant properties are caused first, by the strengthening of the solid solution (ferrite) by such elements as molybdenum and tungsten. Increasing the stability of the solid solution by introducing strong carbide-forming elements (niobium) increases only the resistance to small plastic deformations during creep if the solid solution is not additionally strengthened by other elements (W, Mo). The solid solution is additionally strengthened by the separation of the carbides NbC (Fe, Cr, W, Mo, V)_nC and Me_{23}C_6 .
5. It was established that in steels containing a large amount of chromium (~12%), vanadium plays a favorable role only when its content is not over 0.3%. Any additional increase in vanadium content sharply decreases heat-resistant properties as a result of its transformation in considerable quantities into solid solution (ferrite).
6. The effect of titanium as a strengthening element in the investigated steels was found to be insignificant, even though its effect is increased with temperature.
7. On the basis of the effects of alloying elements on the heat-resistant properties of 12% Cr-Mo steel which have been uncovered in this investigation, two grades of a new blade material for steam turbines operating at 550-600° have been developed and are recommended for industrial testing. These steels contain no nickel and are similar to the austenitic steels of the type EI123 in their heat-resistant properties.

The chemical composition and properties of these new steels at 600° are listed in Table 6.

The impact strength at room temperature for hardened and tempered metal, smelted under either laboratory or industrial conditions, is within the range of 4.5-14 kgm/cm² for the EI757 steel and 10-15 kgm/cm² for the EI756 steel. After aging for 3,000-10,000 hours at 600°, impact strength becomes stabilized at 3-4 kgm/cm².

In the industrial smelting and forging of these steels it was established that their technological properties are entirely adequate. Blades made of the EI756 and EI757 steels have been installed in one of the experimental turbines of the Khar'kov Turbine Plant imeni Kirov.

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Figures

Figure 1. Microstructure of 12% Cr-Mo steel. X500.

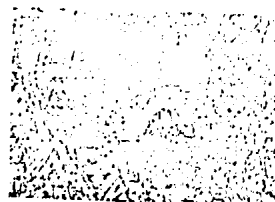


Figure 2. Microstructure of 12% Cr-Mo-V-Nb steel (0.70% Nb). X500.

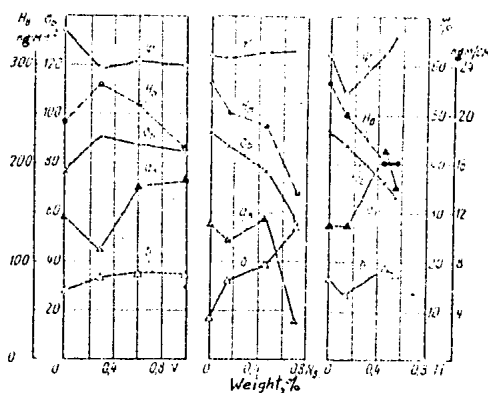


Figure 3. The effect of alloying elements (V, Nb, Ti) on the mechanical properties of 12% Cr-Mo-V steel at room temperature.

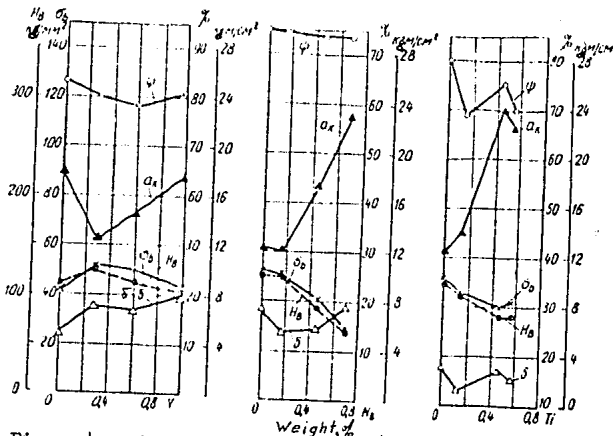


Figure 4. The effect of alloying elements (V, Nb, Ti) on the mechanical properties of 12% Cr-Mo-V steel at 600°C.

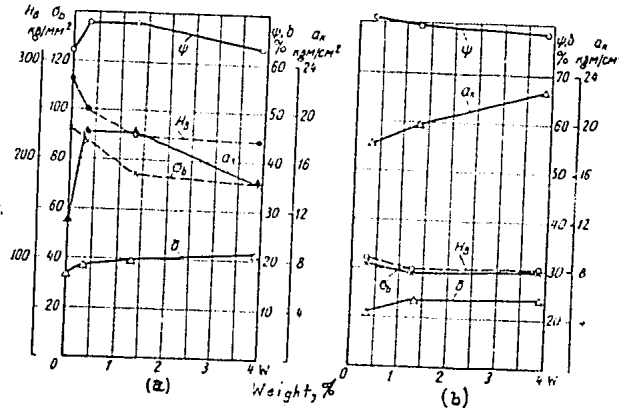


Figure 5. The effect of tungsten on the mechanical properties of 12% Cr-Mo-V steel: (a) at 20°C; (b) at 600°C.

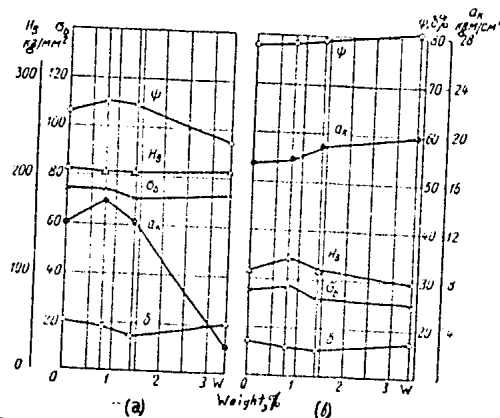


Figure 6. The effect of tungsten on the mechanical properties of 12% Cr-Mo-V-Nb steel: (a) at 20°; (b) at 600°.

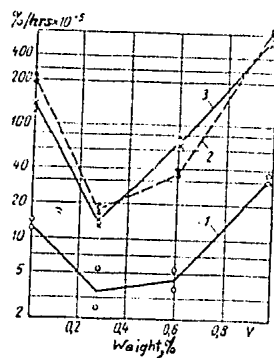


Figure 7. The effect of vanadium on the rate of creep of 12% Cr-Mo-V steel:
 (1) $t = 550^\circ$, $\sigma = 8 \text{ kg/mm}^2$;
 (2) $t = 600^\circ$, $\sigma = 6 \text{ kg/mm}^2$;
 (3) $t = 630^\circ$, $\sigma = 4 \text{ kg/mm}^2$.

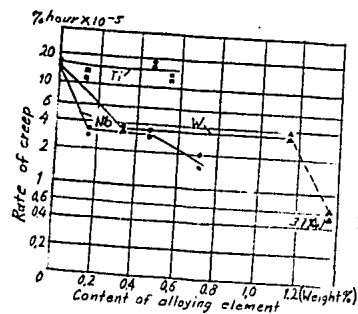


Figure 8. The effect of alloying elements (Ti, Nb, W) on the rate of creep of 12% Cr-Mo-V steel at 600°.

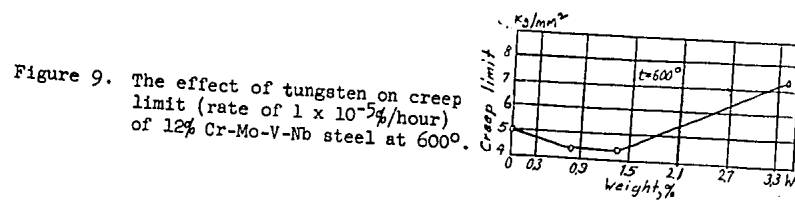


Figure 9. The effect of tungsten on creep limit (rate of 1×10^{-5} %/hour) of 12% Cr-Mo-V-Nb steel at 600°.

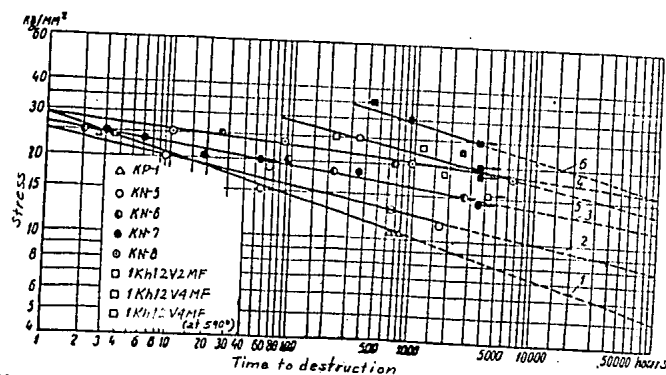


Figure 10. Results of tests for long-time strength of chromium steels at 600°:
 (1) 1Kh12M (KP-1 composition); (2) 1Kh12MFB (KP-5);
 (3) 1Kh12VMFB (KN-6) and 1Kh12V2MFB (KN-7);
 (4) 1Kh12V4MFB (KN-8); (5) 1Kh12V2MF; (6) 1Kh12V4MF.

Table 1. Chemical Composition of Industrial Chromium Steels

Steel Grade	C	Content of Elements (%)						Nb	Other
		Cr	Mo	W	V	Ni			
1Kh13	0.15	12.5-14.5	--	--	--	--		--	--
2Kh13	0.16-0.24	12-14	--	--	--	--		--	--
Kh10S2M (E1107)	0.13	9.72	0.95	--	--	--		--	--
6Kh16M2A	0.60	12-17	2-2.5	--	--	--		--	2.36% Si
4C3	0.06-0.13	11.5-13	--	--	--	--		--	--
H-46	0.2	11	0.6	--	--	0.5		--	--
Rex 448	0.10-0.20	10-13	0.6-0.9	--	0.7	--	0.15	--	--
442	0.20	13	1	--	0.10-0.20	--	0.3-0.6	--	--
1apalloy	0.30	11.50	2.75	1	0.30	0.75	--	--	--
12Cr, Mo	0.15	11.50	3	--	0.25	--	--	--	--
12Cr, Mo, Ni	0.15	11.50	3	--	--	--	--	--	--
12Cr, Mo, V	0.25-0.35	11-12	2.5-3	--	--	1.5	--	--	--
12Cr, W, Ni	0.12-0.17	12-14	0.5	2.5-3.5	0.20-0.30	0.5	--	--	--
12Cr, Mo, W, V	0.19-0.23	11.5-13	0.9-1.1	0.8-1.2	--	1.8	--	--	--
12Cr, Co, W, V	0.17-0.22	11.5-13	0.15	2.5-3.5	0.19-0.27	0.6-0.8	--	--	--
12Cr, Nb	0.13-0.18	11.5-13	--	--	0.19-0.27	0.5	4.5-5.0% Co	--	--
					--	0.5	0.35-0.45	--	--

Table 2. Chemical Composition of Steels Investigated

Series	Composition Index	Contents of Elements (%)										
		C	Cr	Mo	V	Ti	Nb	Ni	Si	Mn	S	P
Vanadium	KI-1	0.13	12.20	0.66	--	--	--	--	0.20	0.77	0.034	0.026
	KI-1	0.16	11.10	0.59	0.28	--	--	--	0.36	0.69	0.025	0.022
	KI-2	0.15	11.36	0.59	0.60	--	--	--	0.36	0.69	0.025	0.014
	KI-3	0.16	11.54	0.59	0.98	--	--	--	0.36	0.69	0.024	0.025
Niobium	KI-1	0.11	11.90	0.69	0.28	--	0.15	--	0.38	0.90	0.030	0.032
	KI-2	0.10	11.90	0.69	0.28	--	0.45	--	0.42	0.89	0.030	0.034
	KI-3	0.11	11.95	0.69	0.24	--	0.71	--	0.56	0.85	0.032	0.035
Titanium	KI-9	0.14	11.32	0.66	0.17	--	0.13	--	0.42	0.67	0.029	0.012
	KI-10	0.15	11.05	0.63	0.20	--	0.46	--	0.48	0.93	0.026	0.010
	KI-11	0.15	10.71	0.53	0.20	--	0.55	--	0.66	0.89	0.025	0.015
Tungsten	KV-5	0.08	11.52	0.69	0.33	0.32	--	--	0.28	0.78	0.029	0.012
	KV-6	0.09	11.65	0.56	0.26	1.15	--	--	0.30	0.77	0.020	0.014
	KV-7	0.09	10.66	0.69	0.25	3.90	--	--	0.34	0.63	0.029	0.012
Tungsten and niobium	KV-5	0.14	12.12	0.66	0.29	--	0.36	0.89	0.32	0.93	0.016	0.022
	KV-6	0.13	11.41	0.73	0.35	0.80	--	1.0	0.17	0.91	0.026	0.025
	KV-7	0.13	11.35	0.70	0.34	1.40	--	0.94	0.28	0.95	0.015	0.027
	KV-8	0.11	11.50	0.70	0.26	3.40	--	0.83	0.14	0.95	0.019	0.028

Table 3. Results of Investigation of Carbide Precipitate of Chromium Steels in Initial State (Hardening + Tempering) and After Aging for 10,000 Hours at 600°

Composition Index	Series	Steel Content (%)		C		Cr	
		Carbon	Alloying Element	Initial State	After Aging	Initial State	After Aging
KF-1	Vanadium	0.16	0.28	6.1	6.7	61.1	60.2
KF-2		0.15	0.60	5.8	5.8	59.5	55.7
KF-3		0.16	0.32	5.9	5.9	58.2	58.0
KH-1	Niobium	0.11	0.15	6.1	6.4	54.1	50.2
KN-2		0.10	0.45	5.9	6.0	41.5	34.3
KN-3		0.11	0.71	8.5	6.6	15.4	12.1
KV-5	Tungsten	0.08	0.32	7.8	6.5	44.8	60.5
KV-6		0.09	0.15	8.6	5.4	43.5	37.4
KV-7		0.09	3.90	7.0	2.1	35.3	23.9
KT-9	Titanium	0.14	0.13	6.0	9.3	56.5	52.4
KT-10		0.15	0.45	8.7	11.5	44.2	40.8
KT-11		0.15	0.55	14.4	15.3	26.8	23.4

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Chemical Composition of Carbide Precipitate in Percentage Weights

Mo		W		V		Nb		Ti	
Initial State	After Aging	Initial State	After Aging	Initial State	After Aging	Initial State	After Aging	Initial State	After Aging
6.0	6.7	--	--	2.9	2.9	--	--	--	--
5.8	6.2	--	--	4.8	4.3	--	--	--	--
5.7	6.3	--	--	7.6	6.3	--	--	--	--
5.1	6.9	--	--	2.3	2.4	9.5	11.0	--	--
3.5	7.8	--	--	1.3	1.4	29.1	32.3	--	--
1.2	6.0	--	--	0.8	0.6	63.0	61.6	--	--
5.9	5.0	5.9	3.2	5.3	4.4	--	--	--	--
5.3	8.4	7.1	18.1	5.5	3.5	--	--	--	--
4.9	5.1	18.0	36.4	2.7	0.8	--	--	--	--
6.4	7.9	--	--	1.0	1.6	--	--	5.3	8.1
5.7	7.1	--	--	0.2	1.2	--	--	18.0	21.8
5.7	6.5	--	--	1.0	1.1	--	--	34.9	37.1

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X-ray Diffraction Analysis Data					
Fe		Mn		Initial State	
Initial State	After Aging	Initial State	After Aging	Carbide Type	Carbide Type After Aging
21.8	21.2	2.1	2.3	Me ₂₃ C ₆	Not determined
22.2	22.0	1.9	2.0		
20.6	21.5	2.0	2.0		
19.0	19.0	3.9	4.1	Me ₂₃ C ₆	Me ₂₃ C ₆
15.8	15.1	2.9	3.1	NbC	NbC
7.3	10.0	3.8	3.1	Me ₂₃ C ₆	Not determined
				NbC	
25.4	16.3	4.9	4.1	Me ₂₃ C ₆	
25.2	24.1	4.8	3.1	Me ₂₃ C ₆	
27.4	30.3	4.7	1.4	(Fe, Cr, W, Mo, V)	id
22.8	17.5	2.0	3.2	nc	Me ₂₃ C ₆ (*3)
19.7	14.1	2.7	3.5	Me ₂₃ C ₆	Not determined
13.0	12.0	4.2	4.6	TiC	
				TiN	
				Me ₂₃ C ₆	
				TiN	

[Adjoins page 16 here.]

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Composition Index	Series	Steel Content (%)		C		Cr	
		Carbon	Alloying Element	Initial State	After Aging	Initial State	After Aging
KN-5	Tungsten and niobium(*1)	0.14	--	10.3	5.4	34.3	30.1
KN-6		0.13	0.8	8.3	6.0	31.4	26.0
KN-7		0.13	1.4	7.7	4.4	29.9	21.7
KN-8		0.11	3.4	5.7	1.9	25.6	16.2

(*1) The column "Steel Content of Alloying Element" lists tungsten content for this series of steel. These steels were aged for 2,000 hours.

(*2) Chemical analysis showed the presence of VC in the KN-3 steel [footnote reference omitted in table].

(*3) Besides the lines corresponding to the carbide Me_2C_6 , the roentgenogram had lines corresponding to the strongest lines of compound Fe_2W . However, because of the great fog it was impossible to confirm that the precipitate investigated contained Fe_2W .

(*4) Besides the lines corresponding to NbC, there were weak diffused lines which could not be identified.

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Chemical Composition of Carbide Precipitate in Percentage Weights

Mo		W		V		Nb		Ti	
Initial State	After Aging	Initial State	After Aging	Initial State	After Aging	Initial State	After Aging	Initial State	After Aging
2.7	2.7	--	--	1.6	1.5	34.8	41.6	--	--
2.7	8.3	2.5	8.3	1.4	1.2	38.3	29.3	--	--
2.4	6.5	3.0	18.0	1.0	0.5	41.6	23.4	--	--
2.6	5.5	13.3	32.7	0.7	0.2	36.2	11.7	--	--

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Roentgenostructural Analysis Data					
Fe	Initial State		Carbide Type	Initial State	
	Initial State	After Aging		Carbide Lattice Parameter	Carbide Type After Aging
12.6	12.6	11.4	NbC	4.46	id
12.2	12.2	18.6			
11.4	11.4	23.8	Me ₂₃ C ₆	10.69	NbC (#4)
13.3	13.3	31.0			

[Adjoins page 19 here.]

Table 4. Chemical Composition of Ferrite in Steels Investigated

Composition Index	Series	Chemical Composition of Ferrite (% weight)										
		Content in Steel (%)		Cr	Mo	V	W	Nb	Ti	Si(*1)	Mn	Fe
		Carbon	Alloying Element									
KF-1	Vanadium	0.16	0.28	9.8	0.45	0.22	--	--	--	0.37	0.65	Remainder
KF-2		0.15	0.60	10.0	0.45	0.51	--	--	--	0.37	0.65	
KF-3		0.16	0.98	10.0	0.45	0.80	--	--	--	0.37	0.65	
KN-1	Niobium	0.11	0.15	11.1	0.61	0.24	--	--(*2)	--	0.39	0.84	"
KN-2		0.10	0.45	11.4	0.64	0.26	--	"	--	0.43	0.85	"
KN-3		0.11	0.71	11.9	0.68	0.23	--	"	--	0.57	0.81	"
KV-5	Tungsten	0.08	0.32	11.2	0.64	0.28	0.26	--	--	0.28	0.74	"
KV-6		0.09	1.15	11.3	0.65	0.20	1.08	--	--	0.30	0.73	"
KV-7		0.09	3.90	10.2	0.63	0.21	3.70	--	--	0.34	0.55	"
KT-9	Titanium	0.14	0.13	10.2	0.52	0.15	--	--	--(*2)	0.43	0.63	"
KT-10		0.15	0.46	10.5	0.55	0.18	--	--	0.16(*3)	0.49	0.90	"
KT-11		0.15	0.55	10.6	0.58	0.19	--	--	0.19(*3)	0.67	0.85	"

Composition Index	Series	Content in Steel (%)		Chemical Composition of Ferrite (% weight)								
		Carbon	Alloying Element	Cr	Mo	V	W	Nb	Ti	Si(*1)	Mn	Fe
KN-5	Tungsten and niobium(*4)	0.14	--	11.8	0.66	0.27	--	--(*2)	--	0.33	0.89	Remainder
KN-6		0.13	0.8	11.1	0.70	0.34	0.77	--(*2)	--	0.17	0.87	"
KN-7		0.13	1.4	11.0	0.67	0.33	1.37	--(*2)	--	0.29	0.91	"
KN-8		0.11	3.4	11.2	0.66	0.25	3.20	--(*2)	--	0.14	0.91	"

(*1) Analytically determined, assuming that part of the silicon is in solid solution

(*2) Element is present only in the carbides

(*3) Data made more precise

(*4) The column "Content of Alloying Element" lists tungsten for this series of steels

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Table 5. Continuous Strength Test Results

Composition Index	Time to Destruction = 11 kg/mm ²	Time to Destruction After Cyclic Stress, = 25 kg/mm ² , hrs	Relative Elongation		Relative Reduction in Area (%)	
			Specimen	Avg	Specimen	Avg
KP-1	622	--	36.4	36.2	72.8	68.9
KF-1	780	--	36.0		65.0	
	Specimens not destroyed at 1,000 hrs	80*				
KF-2	id	51*	37.6	38.4	79.6	80.8
			39.2		82.3	
KF-3	1095	30*	39.5	39.7	84.0	85.6
	1263	36*	40.0		85.2	
KN-1	Specimens not destroyed at 1,000 hrs	--	51.2	52.1	87.5	87.7
		--	53.0		87.9	
KN-2	id	101	32.0	31.7	76.7	78.6
		89	31.4		86.5	
KN-3	284 928	20	39.3	38.3	79.7	79.7
		21	37.3		79.7	
KV-5	Specimens not destroyed at 1,000 hrs	--	49.8	51.7	84.9	83.9
		--	53.6		83.0	
KV-6	id	47	34.6	32.8	72.0	68.5
		49	31.0		62.0	
KV-7	"	19	37.6	36.3	73.8	71.4
		13	35.0		69.0	
		484	16.3	16.2	40.5	36.4
		382	16.0			

Composition Index	Time to Destruction = 11 kg/mm ²	Time to Destruction After Cyclic Stress, = 25 kg/mm ² , hrs	Relative Elongation		Relative Reduction in Area (%)	
			Specimen	Avg	Specimen	Avg
KT-9	1098	--	43.8	42.6	78.7	79.2
	1462	--	41.5		79.8	
KT-10	204	--	54.3	59.2	89.7	90.3
	188	--	64.2		90.9	
KT-11	594	--	40.4	43.8	86.3	86.3
	411	--	47.5		86.3	

* $\sigma = 20 \text{ kg/mm}^2$

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Table 6. Chemical Composition and Properties of New Steels

Steel Grade	Content of Elements							Continuous Strength (10^4 kg/mm ²)	Creep Limit (10^4 kg/mm ²)
	C	Cr	W	Mo	V	Si	Mn		
1Kh12V4MF (E1757)	0.10-- --0.15	10.5-- --12.5	3.7-- --4.3	0.6-- --0.8	0.2-- --0.3	0.20-- --0.35	0.6-- --0.8	14--16	6.0
1Kh12V2MF (E1756)	0.10-- --0.15	10.5-- --12.5	1.8-- --2.2	0.6-- --0.8	0.2-- --0.3	0.20-- --0.35	0.6-- --0.8	12--14	4.5

* * *